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TRANSPORT PHENOMENA IN STRATIFIED MULTI-FLUID FLOW IN THE PRESENCE AND ABSENCE OF GRAVITY

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ABSTRACT

An experiment is being conducted to study the effects of buoyancy on planar stratified flows. A wind tunnel has been designed and constructed to generate planar flows with separate heating for the top and bottom planar air jets emerging from slot nozzles separated by an insulating splitter plate. The objective is to generate planar jet flows with well defined and well controlled velocity and temperature profiles. Magnitudes of velocity and temperature will be varied separately in each flow for both laminar and turbulent flow conditions. Both stably and unstably stratified flows will be studied by changing the temperature distributions in each air stream. This paper reports on the design of the apparatus and initial measurements of velocity and turbulence made by laser Doppler velocimetry.

INTRODUCTION

Transport processes in multi-fluids in the presence and absence of gravity have been studied by numerous researchers. However, most of the previous studies considered the initiation of flow convection and diffusion in a small contained fluid volume that is initially at rest [1,2,3]. The objective of the present study is to investigate the turbulent mixing in stably or unstably stratified flow in the presence and absence of gravity, thereby defining and isolating the effect of buoyance on turbulent mixing.

Under conditions of gravity, stratified shear flows will be stable or unstable depending on the sign of the vertical density gradient, and turbulence will be damped in stably stratified flow, but will be generated by unstably stratified flow [4]. This research describes experiments, in an earth-based test facility, which are planned to be followed up by similar tests under microgravity conditions, and at a range of fluid velocities at which buoyancy and inertia forces are of the same order of magnitude. These experiments with variable buoyancy, forced flows, and gravity conditions, will provide the capability to isolate the effects of buoyancy in stable and unstable stratified shear flows. The turbulence characteristics are determined by laser Doppler velocimetry (LDV), including mean and fluctuating velocity components, Reynolds shear stress, and the temperature field using thermocouples. Particular attention was devoted to designing and constructing a low speed wind tunnel which can generate approximately uniform velocity and temperature profiles in two separate flow streams, that mix downstream from the exit of a two-dimensional nozzle. The earth-based wind tunnel was designated as a "once through" system, whereas the space-based test facility will include a recirculating flow and a cooler, in order to be compatible with the shuttle environment. The establishment of the desired boundary conditions at the wind tunnel exit was accomplished by passing the flowing air through two separate electric heaters, a series of grids, and a converging nozzle, while thermally insulating the two air streams from each other by means of an insulating splitter plate, which is gradually tapered towards the exit.

The overall objectives of this research are:

- To use the reduced gravity environment to improve the understanding of the fundamental physical processes of mixing between layers of fluid of different density and velocity.
- To separate the effects of molecular and turbulent diffusion from gravitational forces during the mixing of two fluid layers.
- To determine the influence of orientation on mixing under gravity and non-gravity conditions.
- To identify non-dimensional parameters that govern the physical phenomena.
- To outline a second phase to this study, in which a dispersed phase will be added to the same flow field.

The understanding of mixing in stratified flows which may be caused by temperature or concentration gradients is important for the understanding of different physical phenomena. This fundamental flow phenomena is encountered in numerous engineering applications in the earth's gravitational field. In atmospheric physics, temperature gradients are the important driving forces which often determine the air quality in urban areas. Thermal stratification in the oceans has long been recognized as a potential energy source which could be exploited. Air and water pollution are often determined by plume hydrodynamics which can be defined by the physics of stratified flow [4].

This research will provide information that will contribute to the basic understanding of the changes in mixing between flowing fluids of different density, as gravity is reduced to zero, and thereby will help minimize any undesirable effects which may result in any of the above listed applications.

DESIGN OF THE EXPERIMENT

In order to study the fundamental physical processes of mixing between layers of shear flows with density gradients, it is necessary to have well established and defined initial flow conditions. To simplify the problem of multiple layers in real flows, a wind tunnel has been constructed in which two co-flowing air streams generated from separated systems make contact in parallel at the edge of a splitter plate. Initially the velocity and density profiles in each flow should be approximately uniform so that there is a sharp step-wise change in velocity and density at the initial interface between the two streams. Uniform velocity profiles can be achieved by convergent nozzles with large contraction ratios. The accelerating flow through the nozzle provides near-uniform velocity distributions. The splitter plate between the flows needs to be thin so that the bluff body interface at the end of the splitter plate is so small that it has a negligible impact on the step change in velocity between the streams. Initial density differences between the two air streams are generated by heating one stream for mixing with the other unheated stream. The upper flow will be heated for stable stratification, while the lower flow will be heated for unstable stratification. Adiabatic conditions of the heated stream before exiting the nozzle are required for achieving initial step-wise density profiles. Therefore, the insulating property and the geometry of the splitter plate which separates the two flows are important concerns in the design.

A low velocity wind tunnel-type facility has been designed and constructed for the experiments conducted under earth-based gravity conditions. Figure 1 shows a 3-D schematic of the experimental apparatus. It consists of two completely separated air systems with a splitter plate sandwiched in between. Each system has the following sections: a first diffuser, an electrical heater, a second diffuser, a honeycomb flow straightener and six mesh screens, and a convergent nozzle. The nozzle only converges in one direction to form a rectangular exit with an aspect ratio of 20. The shape and the dimensions of the nozzle exits are shown in Fig. 2. Two air streams are separated by the splitter plate. Both exits have the same dimensions of 12.7 mm(0.5") in height and 254 mm (10") in width. Each exit cross sectional area is 3225.8 mm^2 .

The flow contraction ratio and the convergent shape are crucial factors in wind tunnel designs, for eliminating flow disturbances and flow separation from the walls. Based on many successful previous applications, the following convergent equations suggested by Rouse and Hassan were selected for this apparatus. The explanation of symbols in the equations is given in Fig.3.

$0 \le x \le x_i$:

$$\frac{R}{D/2} = \frac{D_s}{D} - \left(\frac{D_s}{D} - 1\right)\frac{(x/L_1)^3}{(x_i/L_1)^2} \tag{1}$$

$x_i \le x \le L_1$:

$$\frac{R}{D/2} = 1 + \left(\frac{D_s}{D} - 1\right)\frac{(1-x/L_1)^3}{(1-x_i/L_1)^2} \tag{2}$$

$x_i/D_s=0.3,\ (D_s/D)^2=12.009,\ L_1/D_s=1.2$

Substituting the nozzle exit dimensions in the above equations, gives

$0 \le x \le 91.44$mm: $\quad R=152.4 - 4.568\times10^{-5}x^3$mm (3)

91.44mm$\le x \le$365.76mm: $\quad R=12.7+ 5.076\times10^{-6}(365.76-x)^3$mm (4)

D_s=12D=24H= 304.8mm (12")

x_i=0.3D_s=91.44mm (3.6")

L_1=1.2D_s=365.76mm (14.4")

Aluminum sheets were cut and welded together to form the upper and lower nozzles, which were clamped together, separated by an insulating sharp edged splitter plate with a convergent angle of 2° (Fig. 1). Flanges were welded to the inlet of the nozzles, and connected with the flanges of the honeycomb and mesh screens section. The aluminum honeycomb consists of many small, straight hexagonal tunnels (about 5mm opening width), for straightening the flows and minimizing the velocity fluctuations in the vertical direction. Five stainless steel mesh screens (1.13 mm opening width, 50.7% open area), were installed upstream from the honeycomb, and one downstream from the honeycomb. The velocity fluctuations in the axial direction are reduced by passing through these screens. This section is designed so that the relative positions of each screen and the honeycomb can be easily adjusted, and the number of screens can be increased or decreased, for better flow conditioning.

In order to obtain a step-wise initial density gradient in the two co-flowing air streams, either the upper or the lower flow needs to be heated, depending on the sign of the gradient. Two electrical coil type heaters and a control system were specially designed and manufactured for this purpose. Each heater has a maximum power of 15 kW (45 Amps, 240 Volts, 3 phase) which is sufficient to heat an air flow of 80 CFM to 200°C. Equipped with a precise controlling system, the heater can operate over a wide range of flow conditions. An air flow of less than 1 CFM can be heated to 50°C within a few minutes. Figure 4 shows the internal structure of the apparatus, air supply systems and the heater control system. The air temperature downstream of the heater is detected by a thermocouple and fed back to a digital temperature controller which generates a corresponding 4~20 mAmps command signal to a zero-cross distributive SCR (silicon controlled rectifier) heater power controller. The instantaneous power supplied to the heater is properly adjusted according to the command signal so that the flow temperature can be stabilized at the preset temperature within a short period.

As mentioned previously, the insulating property and the thickness of the splitter plate plays a crucial role in the design. To establish the ideal step-wise velocity and temperature profiles results in contradictory requirements for the splitter plate. A thin and smooth plate will improve the velocity profile but will distort the temperature profile due to increase in heat conduction through the plate. As a compromise, a special design of gradually reducing the plate thickness was selected, as shown in Fig. 4. Marinite-I was chosen as the plate material for its excellent thermal insulating property and high structural strength. Its thermal conductivity and thermal expansion coefficient are 0.12 W/(m°K) at 205°C (0.81 Btu-in/ft^2,hr,°F) and 4.14 $\times 10^{-6}$ 1/°K (2.3 $\times 10^{-6}$ in/in/°F), respectively. The thickness of the plate gradually reduces from 50.8 mm (2") at the heater section to 0.508 mm (0.02") at the nozzle exits. A simple one-dimensional heat transfer model was used to predict the approximate heat flux through the splitter plate. Figure 5 shows the calculated local heat flux from the heated flow (200°C) to the unheated flow (20°C). Inside the nozzle, the substantial decrease of the plate thickness and the increase in the flow velocity due to contraction, results in considerable increase in the local heat flux, which impacts on the temperature profile.

RESULTS

The initial flow conditions for both air streams were measured at the nozzle exits. A 2 component LDV system was used to measure the axial and vertical components of the air flow velocities and velocity fluctuations. A TSI six jets atomiser provides micron size Propylene Glycol droplets which were used as seeding particles mixed in the air flows for velocity measurements. Figure 6 shows the results of the initial axial mean velocity profiles as a function of horizontal position y and vertical position z, while the maximum velocity was kept at 1 m/s. These profiles show very good similarity between upper and lower jets with maximum velocity at the center of each jet and zero velocity at the splitter plate and the top and bottom walls. The profiles are almost identical between y/H= -8 and y/H=8 which demonstrates the extent of two dimensionality of the flow system. The wall effects are also seen near the side walls.

Figure 7 shows the axial mean velocity profile at the center of the 2-D nozzle (y=0) when the maximum flow velocity u_m varies from 1m/s to 5m/s. For the flow velocity of 1m/s, since it is a laminar flow, the boundary layer is thick and the profile is parabolic. As the velocity increases, the boundary layer thickness is reduced, and the profile becomes flatter. At u_m=5m/s, the flow is turbulent, and the profile approaches a plug flow. However, in all the cases, boundary layers with high velocity gradients exist near the splitter plate surfaces due to the wall effects, which hinder the generation of sharp step-wise profiles.

Vertical mean velocity and velocity fluctuations were measured simultaneously with the axial velocity using LDV. Figure 8 shows the results at the center point of the jet (y=0, z=6.35mm) as a function the axial mean velocity u. The vertical mean velocity v and velocity fluctuations u' and v' increase with the flow velocity, but their magnitudes are only a few percent of u. The stream lines at the nozzle exit are smooth and horizontal. The axial rms velocity u' is approximately twice the vertical rms velocity v' at the nozzle exit for all the flow conditions.

The flow velocities and fluctuations at different downstream distances were also measured and are shown in Fig. 9 and 10. As the jet spreads downstream, the axial mean velocity profile widens and relaxes. The maximum velocity begins to decay beyond x/H=6, where the wake is no longer evident in the profiles. At x/H=10, the u profile is Gaussian. The axial rms velocity u' increase progressively with the downstream distance, and shows the highest values in the wake region (x/H<6) and outer edges of the jets due to strong mixing effects. However, the vertical rms velocity v' remains very small in the near field. Beyond x/H=4, turbulence is generated and the values of v' increase with the downstream distance. At x/H=10, both u' and v' are similar. Thus the turbulence can be considered as close to isotropic.

CONCLUSIONS

A wind tunnel with two separately heated air flows, separated by an insulating splitter plate, has been designed, constructed and tested. The exit velocity and turbulence profiles have been measured by LDV. Nearly uniform velocity profiles at the nozzle exits have been achieved. Heat transfer across the splitter plate results in thermal boundary layers inside the wind tunnel that distort the exit temperature profile. The measured turbulence structure, 127mm downstream of the nozzle exit, is close to isotropic.

ACKNOWLEDGMENT

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REFERENCES

1. Koster, J.N. and Sani, R.L. Editors, "Low-Gravity Fluid Dynamics and Transport Phenomena", Progress in Astronautics and Aeronautics, AIAA, Washington, DC, Vol. 130, 1990.
2. Prakash, A., Peltier, J., Fujita, D., Koster, J., Biringen, S., "Convective Instabilities in a Two-Layer Fluid System", AIAA Paper 91-0313, 1991.
3. NASA's Micro Gravity Fluid Physics Workshop, NASA-Lewis, June 15, 1993.
4. Turner, J.S., "Buoyancy Effects in Fluids", Cambridge University Press, 1973.

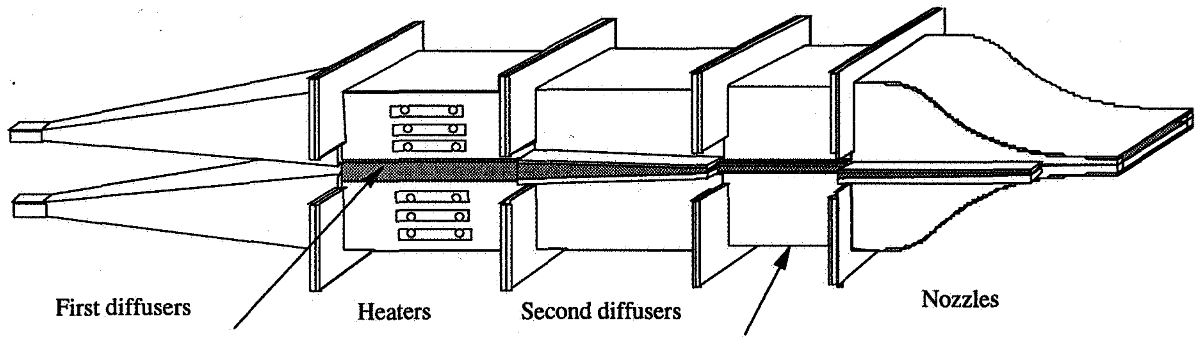

Figure 1 3-D view of the experimental apparatus.

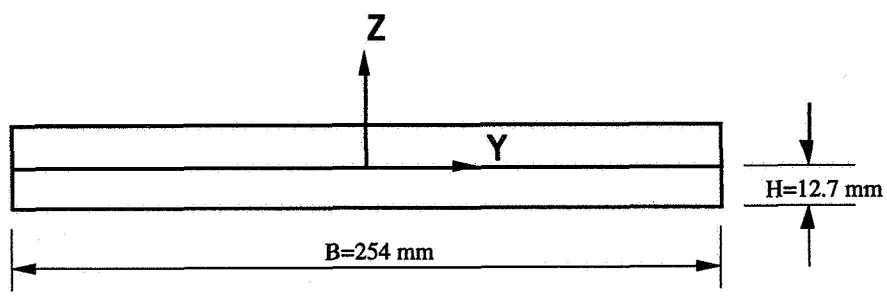

Figure 2 Nozzle exit cross section.

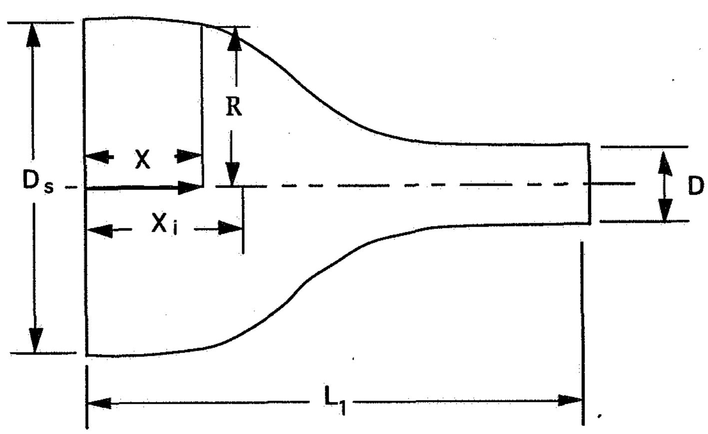

Figure 3 Convergent nozzle [eqs. (1),(2)].

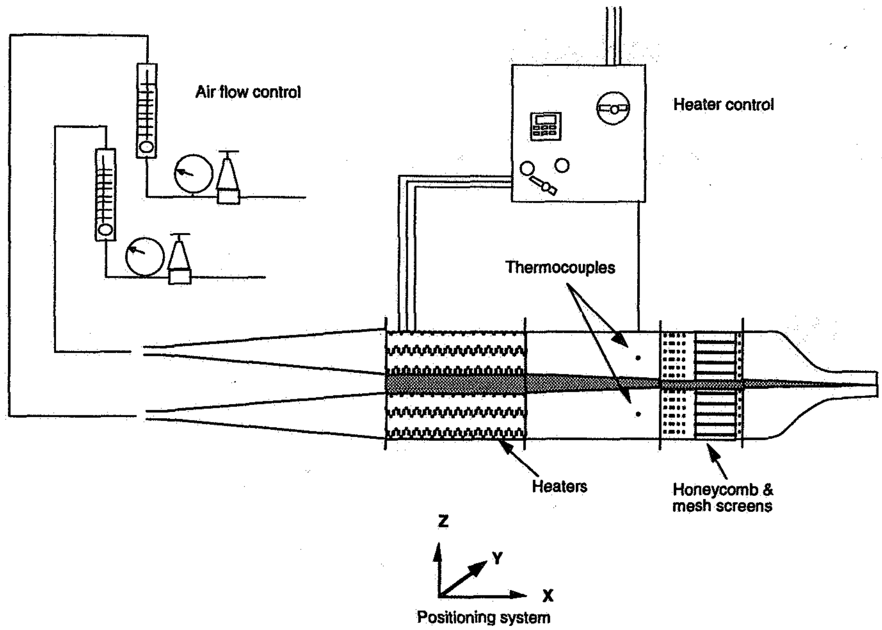

Figure 4 Apparatus and control systems.

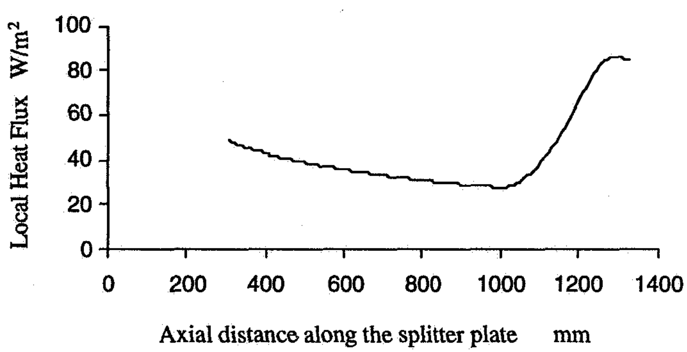

Figure 5 Predicted local heat flux between two flows through the splitter plate.

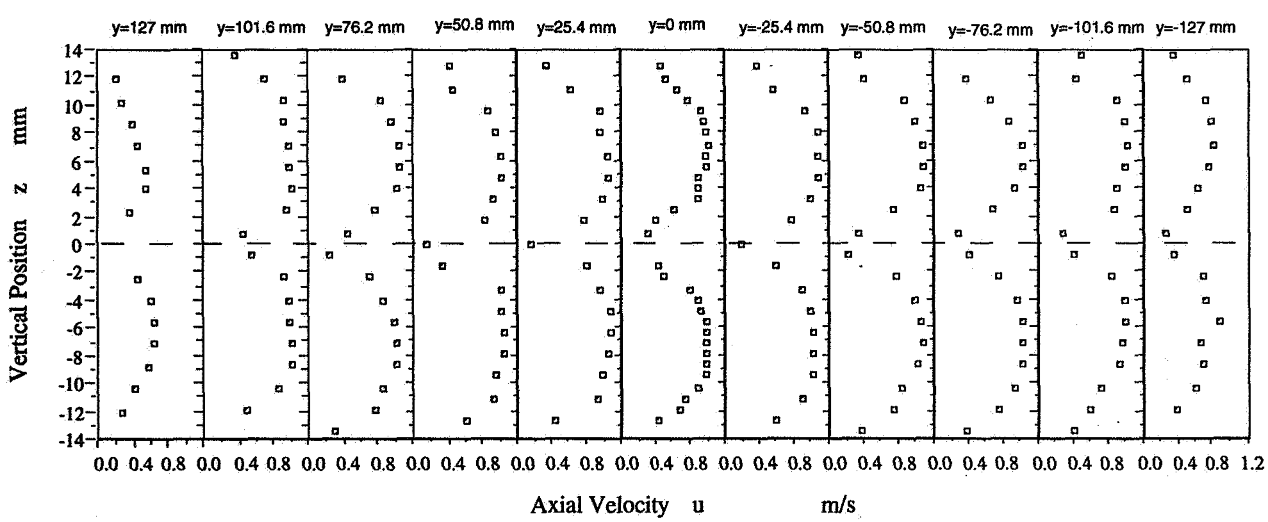

Figure 6 Axial mean velocity u profiles near the nozzle exit as a function of y and z (x=3.175 mm, u_m=1m/s).

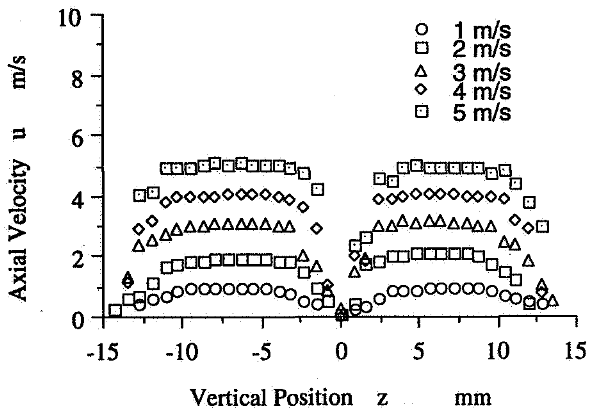

Figure 7 Axial mean velocity profiles at the center position of the 2-D nozzle (x=3.175mm, y=0) for various flow conditions.

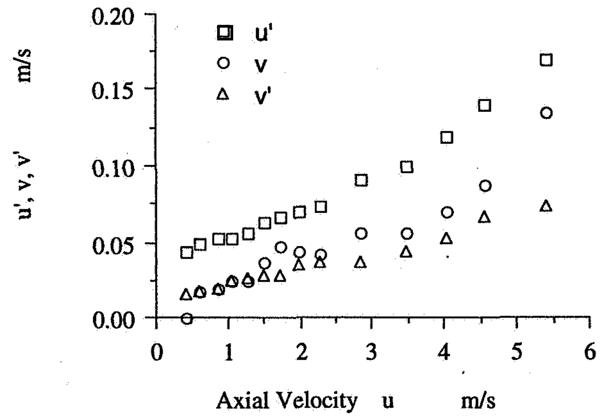

Figure 8 Vertical mean velocity and velocity fluctuations at the center of the flow (x=3.175mm, y=0, z=6.35mm) as a function of axial mean velocity .

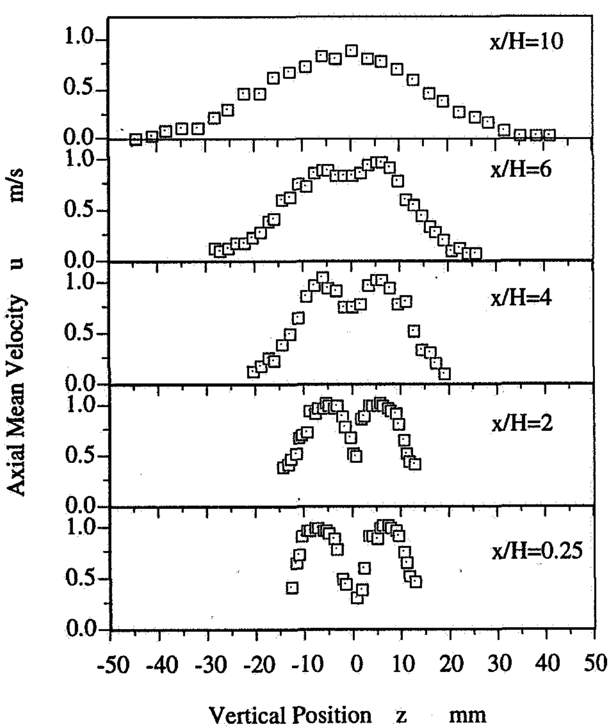

Figure 9 Axial mean velocity profiles as a function of downstream distance (u_m=1m/s).

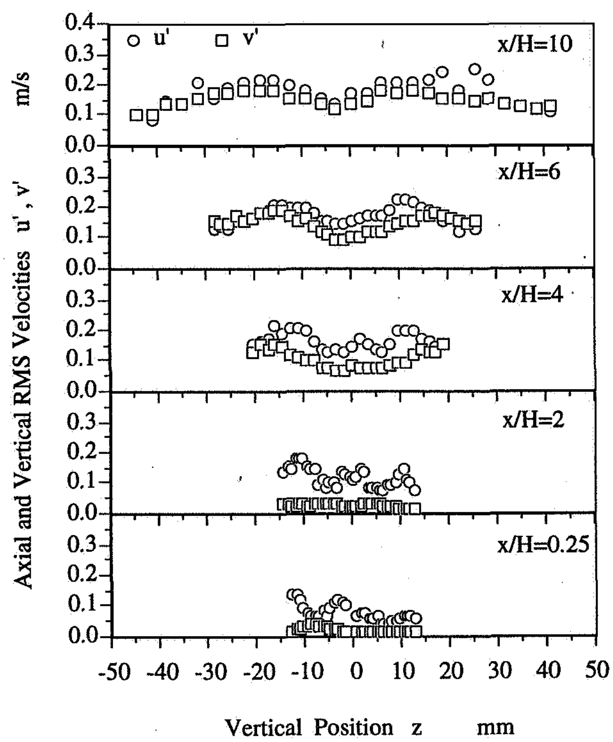

Figure 10 Axial and vertical velocity fluctuations as a function of downstream distance (u_m=1m/s).